Do Production Rates Really Matter?

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Abstract: Production rate is widely assumed to be an important contributor to unit cost -- higher production rates lead to lower unit costs, and vice versa. Examination of published data, however, leads to a more ambiguous picture. This paper examines the impact of rate by functional cost element, including the impact on learning curves. It concludes that production rate impacts are real, but the impacts are uneven and sometimes reveal themselves in surprising ways.

Introduction

It is widely supposed program production costs are influenced by the rate of production. “Common sense and economic theory suggest that production rate should be an important determinant of program costs.” (Gulledge, 1986) Economies of scale suggest that average unit costs will decrease as production volume increases, driven by the amortization of fixed costs and capital equipment over an increasing base of units. In learning curve literature as well, it is frequently asserted that increased production rates beneficially impact the rate of learning. Based on these considerations, many writers recommend cost analysts take production rate in account in cost estimates.

This opinion, however, is not universally held. Thomas Gulledge and Norman Womer write, “This integration [of rate effects into cost models] is overshadowed by the fact that many empirical studies find production rate ‘statistically’ unimportant as a determinant of cost….This lack of statistical evidence is probably the major reason for the slow integration of the learning curve (cumulative output) and the normal economic (output rate) approaches for explaining cost.” (Gulledge, 1986)

This paper looks at the influence of production rate, examines published evidence at a macro- and micro-level, and identifies areas where there is a consensus that production rates influence cost and how they do so. In short, it attempts to answer the question: Do production rates really matter?

The Macro Look

We start with the familiar Crawford improvement curve formula, of the form:

$$Y = MX_1^B \qquad (1)$$

Where

Y = unit cost at unit x_1
M = theoretical first unit (constant)

X_1 = cumulative units produced through unit x
B = coefficient of the cumulative quantity curve

Armen Alchian was the first writer to suggest an alternative formulation of the improvement curve using production rate as a variable. (Alchian, 1950) Rate-augmented improvement curves are usually presented as:

$$Y = MX_1^{B}X_2^{C} \qquad (2)$$

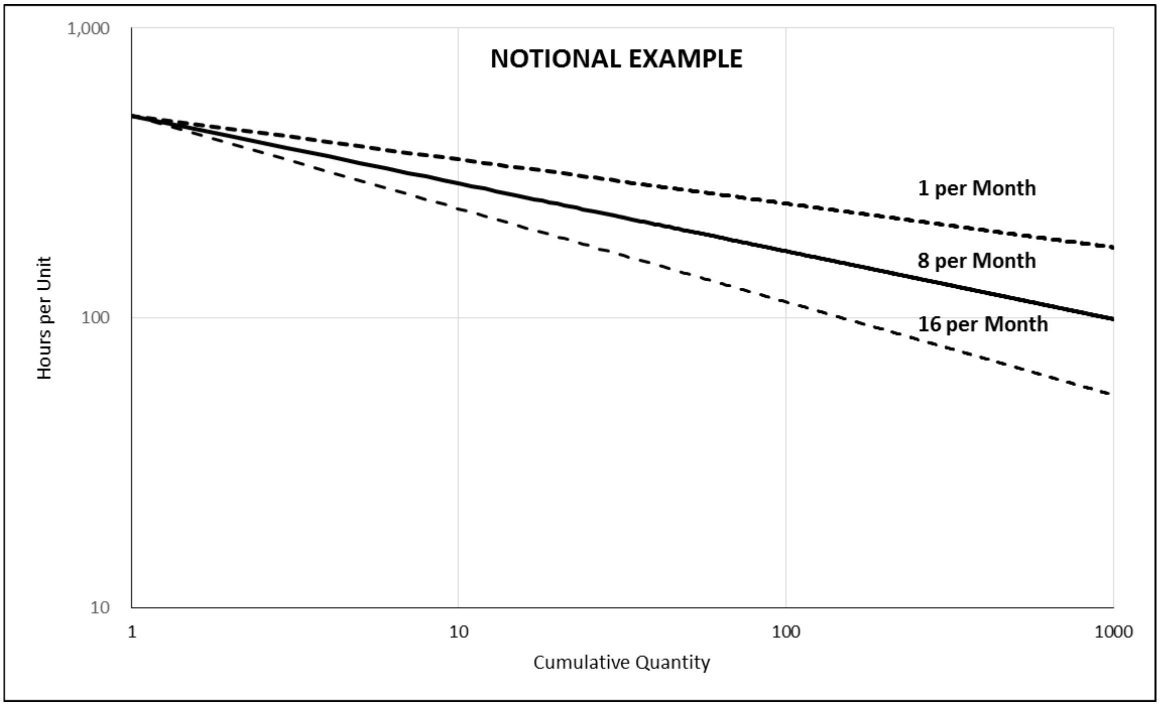
Where in addition to the variables in equation (1) we add:

X_2 = measure of production rate (usually lot size)
C = coefficient of the rate curve

The variable X_2, the rate variable, is usually identified as lot size -- though this approach is open to criticism. One set of critics argue that “aircraft procured in a given year are not produced in the same year, and the time required to produce a lot often changes over the program’s life…For example, lot sizes of 15 and 20 are not good proxies for production rate if the time horizons for the two lots are 12 and 16 months respectively.” (Camm, 1987) Nonetheless, the use of lot size as a proxy for production rate continues, most probably because it is an easily accessible data point from legacy programs vice lot size adjusted for delivery spans or alternate formulations.

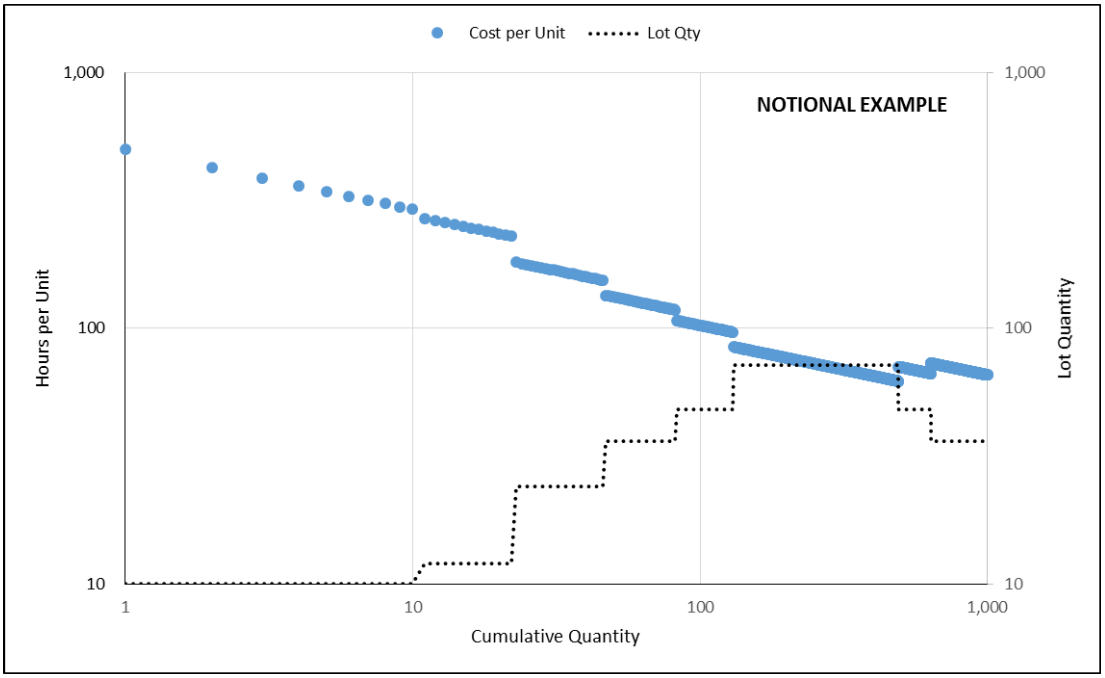
The impact of production rate on improvement curves is usually seen as steepening or flattening the basic curve, depending on whether production rates are increasing or decreasing. The choice of production rate can be seen as an exogenous variable, with its corresponding impact on cost performance as follows:

Exhibit 1.



If we combine this with cumulative quantity, it yields a segmented improvement curve with slopes steepening or flattening as production rates increase or decrease, as follows:

Exhibit 2.



The Macro Look

One of the most frequently cited studies of production rate impacts is the work of John C. Bemis. (Bemis 1981, 1983). Bemis studied 20 defense systems and correlated unit price with cum quantity and production rate to fit equation (2). A summary of his results is shown below.

Exhibit 3.

	Individual Regressions				Multiple Regression		
	Quantity/Cost		Rate/Cost			Quantity	Rate
System	R^2	Slope	R^2	Slope	R^2	Slope	Slope
Aircraft A	0.949	72.1%	0.543	71.4%	0.974	73.1%	97.5%
Aircraft B	0.924	87.7%	0.852	78.6%	0.948	77.2%	**
Aircraft C	0.876	76.0%	0.918	68.5%	0.995	87.3%	79.5%
Aircraft D	0.498	76.9%	0.769	61.6%	0.923	88.2%	68.0%
Aircraft E	0.984	67.8%	0.992	58.7%	0.997	90.5%	67.2%
Aircraft F	0.461	67.0%	0.945	52.8%	0.994	86.6%	57.3%
Aircraft G	0.988	75.8%	0.972	58.7%	0.999	84.0%	81.4%
Aircraft H	0.929	70.7%	0.664	66.7%	0.971	74.4%	91.4%
Helicopter	0.992	83.1%	0.766	81.9%	0.997	83.8%	89.3%
Jet Engine A	0.943	72.6%	0.425	74.6%	0.984	75.0%	92.0%
Jet Engine B	0.941	69.8%	0.228	76.3%	0.988	71.4%	89.5%
Missile A	0.949	66.0%	0.856	52.5%	0.974	65.1%	**
Missile B	0.724	85.4%	0.214	84.2%	0.873	82.3%	**
Missile G&C	0.468	*	0.672	89.4%	0.981	**	90.7%
Missile G&C	0.672	60.0%	0.980	62.8%	0.996	91.9%	59.4%
Ordnance Item A	0.869	86.6%	0.387	93.2%	0.964	88.1%	97.0%
Ordnance Item B	0.945	76.6%	0.346	*	0.978	97.5%	**
Radar Set A	0.585	87.7%	0.814	86.0%	0.990	93.1%	88.8%
Radar Set B	0.615	94.7%	0.757	88.8%	0.890	98.9%	91.6%
Tracked Vehicle	0.490	*	0.752	88.7%	0.963	**	90.7%
Mean	0.790	76.5%	0.693	73.4%	0.969	83.8%	83.2%

* Positive Quantity/Cost or Rate/Cost Slope
** Addition of Rate Variable Changed Sign to Positive in Multiple Regression

Bemis's study appears to show the benefit of adding a production rate variable to the standard improvement curve model. The best fit statistics as measured by R^2 are markedly improved by combining cumulative quantity and production rate in a single regression equation as opposed to taking each individually. For example, the calculated mean R^2 of 0.969 for combining cum quantity and rate is superior to the individual statistics for quantity only (R^2 = 0.79) or production rate (R^2 = 0.693).

But beneath the placid surface of R^2, turmoil lurks. In four cases where cum quantity and production rate have been run as part of a single equation, the rate slope is *positive*, implying that increasing production rates produces a *higher* unit cost. In two cases, the cumulative quantity slope is *positive*, implying that building more units over time produces a *higher* unit cost. Thus, in six of the 20 cases studied, the general implications of a rate augmented model -- that higher cum quantities and increased production rates reduce cost -- are not supported by the evidence.

Moreover, there is a substantial degree of variation in the calculated slopes themselves. In the eight aircraft cases, for example, the reported production rate slope varies from 57.3% to 97.5%, excluding the case where the slope is greater than 100%. With such a wide range of choices, it is difficult to know what to use for future projections or for an analogy to estimate the next program. It is especially hard to say with confidence exactly how much production rate actually impacts program cost – the answers in the data lie between “very significantly” to “not very much at all.”

Cox and Gansler performed a similar analysis for tactical missile programs, as shown in Exhibit 4:

Exhibit 4.

	Qty	Rate
Sparrow (1st source)	84.6%	98.5%
Sparrow (2nd source)	87.4%	92.3%
Bullpup	82.3%	100.4%
Tow	99.1%	100.7%
Sidewinder	95.5%	81.9%
Mean	89.8%	94.8%

Again we will see similar results. While the quantity and rate slopes for Sparrow and Sidewinder conform to expectations, the rate slopes for Bullpup and Tow are positive -- implying counterintuitively that higher production rates *increase* production costs.

These two cases provide a useful illustration of why the rate augmented model is not universally embraced. Critics of the rate model have identified four problems with it.

1. The independent variables of cumulative quantity and production rate are often highly correlated and exhibit significant multicollinearity, often producing coefficient estimates which are unreliable and frequently of the wrong sign.
2. The production rate variable, even when it is of the 'right' sign, is often not statistically significant at accepted thresholds of 90% or 95% significance.
3. There is potential measurement error surrounding the definition of production rate as noted earlier, particularly the use of lot size to measure rates.
4. There are theoretical objections to the model. The rate augmentation model is commonly presented absent any kind of capacity constraint. Carried to its logical conclusion, therefore, the model would conclude that the lowest cost solution is for a contractor to produce all the units in the production program in a single production lot. (Gulledge, 1986)

There are two possible explanations for the positively sloped rate slope sometimes observed in the data. The first and most common explanation is that the observed positive slopes are symptoms of collinearity between the cumulative quantity and the production rate variables. This usually leads researchers to attempt to 'fix' the data, usually through statistical techniques like ridge regression. Gulledge and Womer, on the other hand, argue that a positively sloped rate slope is not a statistical anomaly, but evidence that the firm is producing in the region of diminishing returns on the short-run cost curve. The upward pull on costs from production rates is overcome by the dominant learning effect – in short, cumulative quantity trumps rate, continuing to force costs down even though the rate variable has a positive slope. (Gulledge, 1986)

The Micro Look

Another criticism levied on the rate augmentation model is that the sources of rate benefit are not very well understood. Therefore, it would be helpful to look at the published research on rate impacts against particular cost elements.

Strathman (1973) suggests six rate-related factors which impact cost, both positively and negatively:

- Engineering costs are not related to quantity.
- Higher production rates require more tooling.
- Setup hours are amortized over larger order sizes as production rates increase.
- New workers affect assembly performance negatively, at least in the short-term.
- Quantity discounts reduce unit procurement costs.
- New workers are typically paid less, reducing production labor rates.
- Additional business volume reduces overhead rates.

We will consider these as we go through cost elements where we might expect a rate impact, beneficial or otherwise.

MANUFACTURING LABOR

Since manufacturing labor is overwhelmingly the focus of improvement curve literature, it is not surprising that it is the area where the costs and benefits of production rate have been most carefully studied.

For proponents of rate augmentation models, higher production rates:

- Present an operator more opportunities to learn within a given time period; or said differently, the shorter interval between units allows him to retain more 'know-how' from unit to unit.
- Force more specialization of labor, allowing a given operator to gain more expertise in a given task.
- Create greater standardization.
- Incentivize greater investment in labor saving machinery.
- Create a greater sense of urgency on the production line, motivating operators to work faster.
- Allow setup times on a given shop order to be amortized over a greater number of units. (Congleton, 1977)

In turn, these benefits would be reversed in case of a production rate decrease, i.e., workers have less opportunity to learn and longer intervals between units, potentially losing learning, etc.

On the other hand, a case can be made that rate changes will affect unit cost adversely, especially in the short run. For example:

- Production rate increases require new personnel who must be transferred from other programs or hired off the street. In either case, there is a period of learning before these employees reach the productivity of their peers.
- Production rate decreases require employee layoffs and reassignment of remaining personnel to new responsibilities, which also requires an adjustment period. This impact is particularly acute in a union shop where "bumping" occurs.

It is important, therefore, to distinguish the difference between long-term and short-term impacts of rate changes.

Manufacturing: Short-Term Impacts

There is little published research on short-term impacts associated with production rates. Short-term impacts are by definition transitory and do not carry over a large number of units; therefore, the typical analysis of lot costs provides little insight. The research that has been performed is generally proprietary studies assembled by contractors and, therefore, is unavailable to the public.

Nonetheless, there is substantial anecdotal evidence which suggests that variations in production rates can produce significant short-term impacts. The commercial jetliner industry provides some excellent examples. Boeing attempted to significantly increase its 737 and 747 production rates in the late 1990's by hiring thousands of new workers. Boeing's 1997 annual report laments: "In pushing to double production rate to meet heavy demands of a booming market, we experienced serious cost and schedule problems." (Boeing, 1997) A front page story from *The New York Times* that same year describes this further:

"In early October, overwhelmed by thousands of foul-ups, Boeing temporarily halted production of the 747 as well as the smaller 737….Boeing had to scramble to find people to build its airplanes, hiring 32,000 workers in the last 18 months. Despite what they describe as an aggressive training program, with five weeks of instruction before starting work, Boeing executives conceded that many new workers were still not fully prepared. 'We have incurred the penalty of these people learning' on the job, said Gary R. Scott, the vice president in charge of producing the 737 and 757." (Zuckermann, 1997)

Interestingly, Boeing experienced similar issues on the same 747 production line 30 years earlier:

"At the time production was starting on the 747, Boeing could not find enough workers in the Seattle area and was forced to recruit intensively. Of the workers hired, less than half developed into normally productive workers. Labor hours per aircraft increased as production rate and cumulative quantity increased, i.e., the learning curve had a positive instead of a negative slope." (Large, 1974)

Yet another case comes from McDonnell Douglas during the same time period, as it struggled to keep up with demand for a stretched DC-8 as well as an increase in DC-9 production. (Large, 1974)

Less obvious is the short-term impact of a production rate decrease. Senior employees frequently have so-called 'bumping' rights in union contracts. These contracts require personnel reductions to be made on the basis of seniority or a last-in, first-out basis. If a senior employee's position is eliminated, he has the right to 'bump' a junior employee and take his job provided the senior employee is qualified. The 'bumped' employee may in turn have the right to 'bump' a more junior employee, and so on. In this way, a single layoff might create as many as four or five employee moves. This can create significant turnover among crews with reassigned employees learning new tasks or re-learning tasks not performed in perhaps months or years. This has a negative impact on worker productivity and unit costs.

These impacts do not last forever. As employees become accustomed to their new assignments, their productivity improves and unit costs begin to decrease again. Nonetheless, in the short term any change in the production rate to an established production line will increase costs. "The disruptive effect is transient, but 'transient' can mean months rather than days or weeks." (Large, 1974)

Manufacturing: Long-Term Impacts

We turn now to the long-term impacts of production rate changes on manufacturing cost performance. There is no shortage of papers which have examined this subject. A number have concluded production rates have a significant long-term impact on manufacturing unit costs. These papers include:

- Johnson – analysis of rocket motors (1969)
- Orsini – analysis of C-141 aircraft (1970)
- Groemping – analysis of A-7, F-4, A-4, F-86, F-102, F-8 aircraft (1976)
- Smith – analysis of F-4, F-102, KC-135 aircraft (1976)
- Congleton – analysis of T-38/F-5 aircraft (1977)

Yet the conclusion that good cost modeling requires attention to production rates is not universally accepted. The creator of the rate augmentation equation, Armen Alchian, summarily dismissed his own creation, concluding it did not provide any better fit than the usual improvement curve. (Alchian, 1950) In his 1956 study of improvement curves for RAND, Harold Asher argued the effect of production rate is of "minor importance, within a certain range, and definitely subordinate to the effect of cumulative production." After examining post-World War II fighter aircraft, he concluded: "It is apparent that similar unit man-hour cost was experienced by producers having widely different rates of production." (Asher, 1956). Similarly, a study of machine-tool manufacturer by W. Z. Hirsch concluded there was no significant relationship between lot size and unit cost. (Hirsch, 1952). Likewise, E. B. Cochrane, author of one of the most influential books on improvement curves, concluded, "There is little evidence for a consistent relationship between slope and product complexity or production rate….The argument for a direct relationship between slope and production rate rests on a spurious relationship with mass production costs….Fundamentally the sources of cost reduction available as a long cycle operation is planned for high production rates will <u>reduce</u> or <u>flatten</u> the amount of learning slope." (Cochrane, 1968)

So which set of experts should we listen to? The picture becomes further muddied when we examine the studies assembled by proponents of rate augmentation models and discover analytical issues or problems with each.

Johnson – In his analysis, Johnson used data from four rocket motor production programs across three companies. In three cases, the R^2 improved as a result of including cumulative quantity and production rate. Poor fits were reported in the fourth case, which Johnson attributed to labor charging inconsistencies. Johnson's model uses an unusual format regressing direct labor hours per month against a linear function of production rate (equivalent units per month) and a logarithmic function of cumulative units produced. Besides R^2, no other statistical information from the regression was provided, making it impossible to determine if the resulting coefficients were statistically significant. (Johnson, 1969)

Orsini – Following Johnson's lead, Orsini applied a similar model to the C-141 production program. He concluded, like Johnson, that production rate was a significant factor. Orsini's analysis was criticized by RAND in its 1974 analysis of production rate impacts. Regressing the same C-141 data used by Orsini, RAND arrived at a different conclusion. Using a two independent variable regression, they concluded that "including production rate in this way appears to give only slightly better results than can be obtained by using quantity only. The slight increase in R^2 is probably the statistical effect of adding another variable to the equation." (Large, 1974)

Groemping – This analysis of the A-7, F-4, A-4, F-86, F-102 and F-8 programs found data issues with multicollinearity, which Groemping attempted to fix with the use of ridge regression. Ridge regression uses a different optimization technique than ordinary least squares. It trades bias against a hopefully larger reduction in variance of the least squares estimators by introducing the ridge regression variable k. Its use remains controversial among statistical practitioners. The value of k is not a given and is often a guess. (Kmenta, 1986) "The ridge technique essentially consists of an arbitrary numerical adjustment to the sample data," argues Johnston, "and one does not really know how to interpret the resultant estimators." (Johnston, 1984) A third text argues that the estimators have unknown distributions and, therefore, hypothesis testing cannot be legitimately performed. (Kennedy, 1997)

Smith – Based on an analysis of F-4, F-102, and KC-135 aircraft, Smith concluded rate was a significant contributor based on a higher R^2 for the rate augmentation model as opposed to the traditional learning model. But slopes were sometimes positive and Smith himself said a generalized cost model should not be attempted since model coefficients varied significantly. (Smith, 1976)

We may add to this studies which concluded that rate was not a significant factor in long-term manufacturing unit cost reduction.

Bourgoine & Collins – In their study of the A-10, they concluded "the production rate variable does not explain in a statistically significant amount of additional variation in direct labor hour requirements for A-10 aircraft production." (Bourgoine, 1982).

Benkard – In Lamar Benkard's study of organizational learning and forgetting on the L-1011 commercial jetliner, Benkard included line speed, a measure of production rate, as one of his independent variables. The line speed variable was positive (implying unit costs increased as production rates increased) but in any case was not statistically significant. (Benkard, 2001)

Large – In a controversial 1974 analysis, RAND concluded that most cost elements, including manufacturing, were not significantly impacted by production rate impacts. The industry and government responses to the draft report were so vigorous that RAND took the unusual step of directly incorporating many of them into its final report, providing a fascinating running commentary of acceptance or disagreement with its final conclusions.

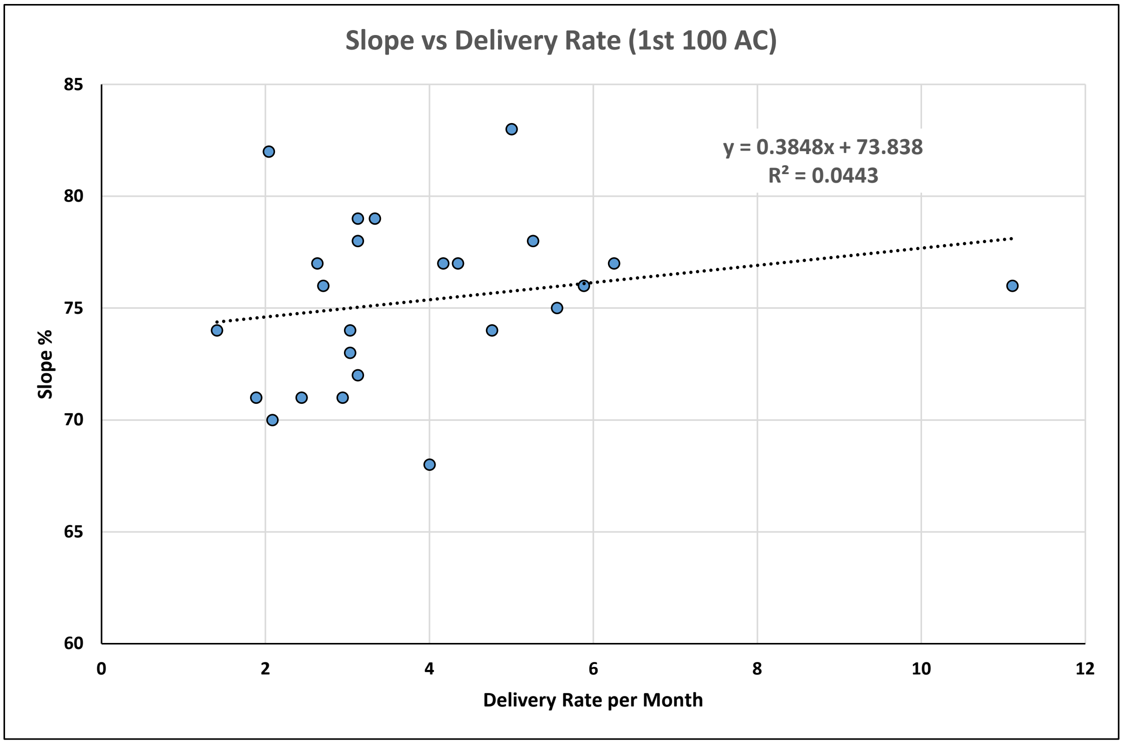
Looking at seven production programs (F-102, F-104, B-58, A-4, C-124, F-86D, KC-135), RAND concluded: "In none of the programs did the inclusion of production rate improve the coefficient of determination,

R^2, by as much as 1 percent over what was obtained using cumulative quantity alone. In four cases the contribution of rate was found to be statistically significant, but in one of those cases, the C-124, the sign of b was positive instead of negative, implying that labor hours per unit increase as rate increases." Based on these results, "it is difficult to conclude that rate of output has a predictable or important effect on labor hours." (Large, 1974)

The RAND report also struck hard at the relationship between manufacturing slopes and production rates. In an analysis of 24 military aircraft, RAND examined the assumption that programs with higher production rates would evidence steeper manufacturing learning slopes. Unusually RAND did not use lot size, but instead used acceptance spans – the number of months it took a given program to reach its 100th aircraft (and in a secondary analysis, the 200th aircraft).

The data for the 24 aircraft is graphed in Exhibit 5 below. For simplicity, an average delivery rate per month has been calculated by dividing 100 aircraft by the number of months to reach that milestone. Once plotted, it is clear there is no apparent relationship manufacturing learning slopes and production rates:

Exhibit 5.



Confirming an earlier theorem of Asher in his 1956 study, RAND did, however, find a fair relationship between the steepness of the learning curve slope and the theoretical first unit (TFU) cost. The higher the TFU, RAND found, the steeper the subsequent learning curve slope. Attempting to combine TFU costs and production rate together as explanatory variables into a single model, however, did not yield the desired results – again, the relationship between cost and production rate was not statistically significant. (Large, 1974)

One area where RAND did not dismiss a potential long-term impact was the area of setup costs for fabrication. Setup is the time it takes to ready machines, tools, details and accessories for a production job and teardown after the run is complete. Setup is typically performed once in a production run and, therefore, is the same cost if the shop order requires one or one hundred parts to be fabricated. At higher production rates, fabrication departments typically release larger quantities against a shop order, allowing setup hours to be amortized over a larger number of units and reducing unit costs. Slashing production rates, by contrast, leads to higher unit costs by causing setup to be allocated across fewer units. RAND pointed to the example of F-4 production when McDonnell Douglas was forced to reduce production rates from 58 aircraft per month back to 6 per month after approximately 4,500 aircraft had been delivered. Setup costs which had averaged 2,000 hours per unit exploded to 7,000 hours per unit. (Large, 1974)

It is an open question, however, whether the shift in manufacturing processes over time away from sheet metal fabrication toward the intensive use of composites has largely mitigated the impact on setup. Unlike older manufacturing processes, composite parts are typically released at one part per shop order – regardless of production rate. This negates both the benefits and penalties related to setup amortization and rate. Given that composites now make up 25%-50% of the most recent military and commercial aircraft by structure weight, the potential benefits of reduced setup is no longer as important as it might have been in the 1960's and 1970's.

Younossi - More recent studies have concluded that production rates do not significantly affect manufacturing unit costs over the long run. In its 2001 study using the Military Aircraft Data and Retrieval (MACDAR) fighter aircraft database (AV-8B, F-14, F-15, F-16, F/A-18), RAND used manufacturing hours collected by lot and lot size to calculate an average cumulative quantity slope of 80% and rate slope of 97%. Such a flat slope for production rate suggests a relatively small impact for changes in production rate on manufacturing unit cost. Moreover, RAND concluded that the production rate variable (measured in this case by lot size) was not statistically significant at either the 90% or 95% levels. (Younossi, 2001) When a coefficient estimate is not statistically significant, we cannot say with confidence that the real impact of the variable (in this case, production rate) is not zero.

So what is our conclusion about the relationship between manufacturing unit hours and production rates? In the short term, the evidence seems to demonstrate the (mostly negative) impacts of increased or decreased production rates on unit cost. In the long term, the picture is far less clear. Perhaps the 1974 RAND study stated the issue best: "The somewhat unsatisfactory conclusion was that the rate of output does have an effect as generally assumed, i.e., an increase in rate causes a decrease in hours, but that the effect is too slight to be measured using the gross data available." (Large, 1974)

SUPPORT LABOR FUNCTIONS

Since the initial publication of T. P. Wright's analysis of improvement curves in 1936, virtually all the published learning curve analysis has focused on manufacturing hours, with very little analysis of support labor hours. This is a curious omission for two reasons. First, there is every reason to suppose that many of the factors which influence learning on the shop floor (worker and supervisor knowledge, process and tool improvement) similarly influence the productivity of support labor. Second, support labor hours are often as substantial as direct touch labor hours, and sometimes more so. In the MACDAR fighter database studied by RAND, support labor ranged from 50% to 120% of the touch labor hours depending on the production phase. (Younossi, 2001)

However, companies have different accounting structures with sometimes very different definitions as to what constitutes direct versus indirect labor. Moreover, those companies often differ as to which organizations perform which tasks. (For example, is the release of planning and work instructions for parts a function of the engineering organization or part of the tooling organization? Many companies will answer differently.) This substantially complicates data collection; and where data collection is difficult, analysis is always lagging. It is not surprisingly there are relatively few analyses of how production rates impact support labor functions. In the following sections, we will review what is available.

NON-RECURRING TOOLING

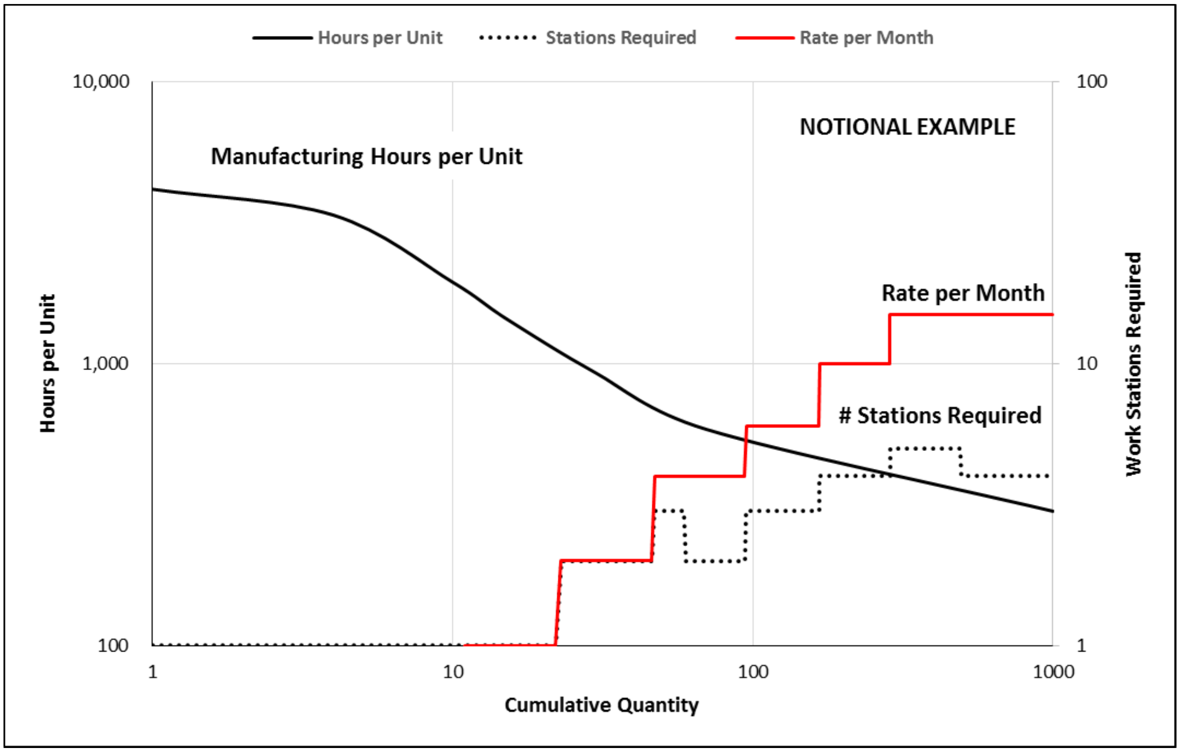
Tooling covers the fabrication and subassembly of major jigs, dies, fixtures, work platforms and test equipment. It usually excludes capital equipment such as machines and robots. In many companies, the tooling function is also responsible for manufacturing engineering as well as the development and release of manufacturing planning, tool designs and numerical control programs.

Non-recurring tooling covers the initial release of tools as well as duplication of tools to achieve a given production rate. In the case of rate tooling, the relationship between non-recurring tooling and production rate is plain. As production rates increase, additional work stations will be required at various trigger points, in turn requiring additional sets of tools. The standard industrial engineering formula for determining the number of work stations makes production rate a key variable along with manufacturing hours per unit and crew load:

$$\frac{[Hours\ per\ Unit\ \div (Crewload\ x\ Hours\ per\ Day\ x\ Shifts\ per\ Day)]}{Days\ Worked\ in\ Month\ \div Production\ Rate\ per\ Month} = No.of\ Stations\ Required$$

Exhibit 6 shows a notional example of how duplicate tooling corresponds with production rate changes. In the example, the number of work stations increase as production rates increase but not in a one-to-one fashion. The reduction of manufacturing unit hours over time along the improvement curve allows some increase in production volumes to be accommodated without adding additional tools.

Exhibit 6.



One commentator in RAND's 1974 analysis summarized the relationship nicely: "[I]t is not to be expected that production rate will uniformly influence the cost of non-recurring tooling, but rather introduce step increases in cost at those points where production rate exceeds the rate capability of a given complement of tooling." (Large, 1974) This is sometimes modeled parametrically, however, with a more or less smooth line. One source describes industry practice in parametric estimates as assuming that duplicate tooling increases tooling cost as a function of the square root of the production rate. (Kenyon, 1973) Likewise, based on analysis of 11 military aircraft, Levinson fitted cumulative tooling hours to the form:

$$\left(\frac{T_a}{T_b}\right) = \left(\frac{R_a}{R_b}\right)^{0.4}$$

where production rates at points a and b on a cumulative tooling hour plot are represented by R_a and R_b, respectively, and cumulative tooling hours are represented by T_a and T_b, respectively. (Levinson, 1966)

SUSTAINING TOOLING

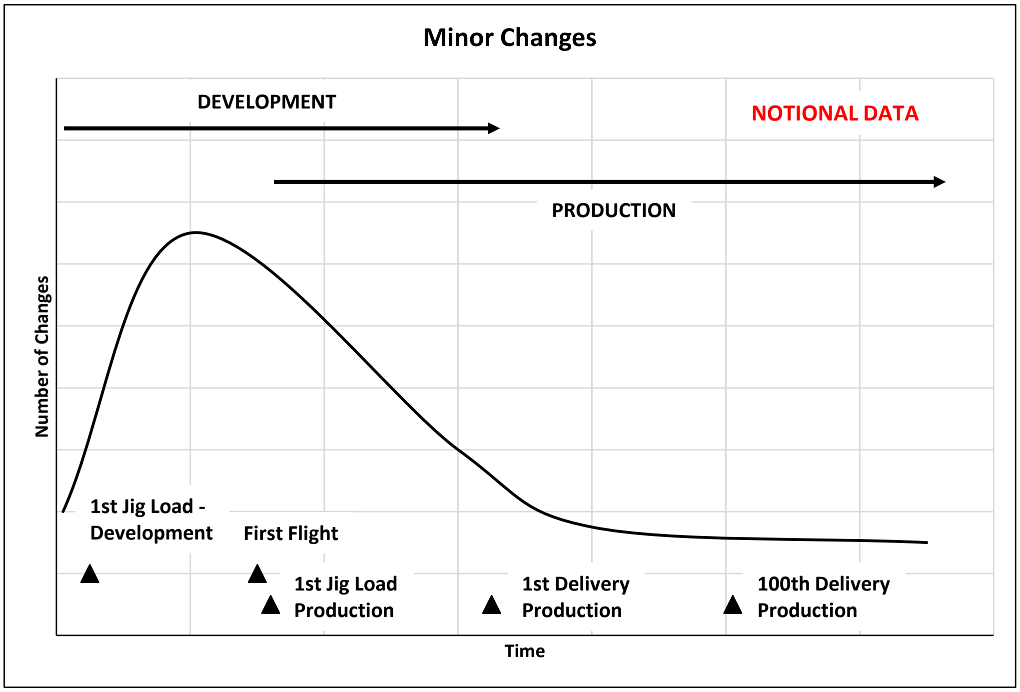
Recurring tooling typically coves the maintenance of tools, planning and numerical control (NC) programs, the incorporation of minor changes, and refurbishment and replacement of worn and damaged tools. It also includes the manufacturing engineering and planning tasks to support these efforts.

Because there is a significant overlap between recurring (or sustaining) engineering and tooling, it may be useful to think of these two together. Sustaining engineering and tooling cover a variety of common tasks, albeit with different personnel and skill sets:

- Material Review Board (MRB) disposition
- Investigation of quality non-conformances
- Incorporation of minor (Class II) engineering changes
- Floor liaison / investigation of "squawks"
- Maintenance of drawings, tools, designs and planning

In this list of tasks, it is apparent that some tasks will be influenced primarily by cumulative experience, others by production volume. For example, for minor engineering changes, cumulative time or experience is the primary driver of improvement. Exhibit 7 shows a typical pattern for the number of engineering changes on an aircraft program. As initial subassembly and assembly begins, errors in tooling and detail part manufacture are discovered. Change releases continue to mount as equipment and systems are installed and checked out and flight test begins on the first aircraft. However, there is a rapid reduction of engineering changes after the initial aircraft are built, requiring fewer manufacturing engineering, planners and design engineers to create and process these changes. Eventually the number of engineering changes reaches a steady state and levels off.

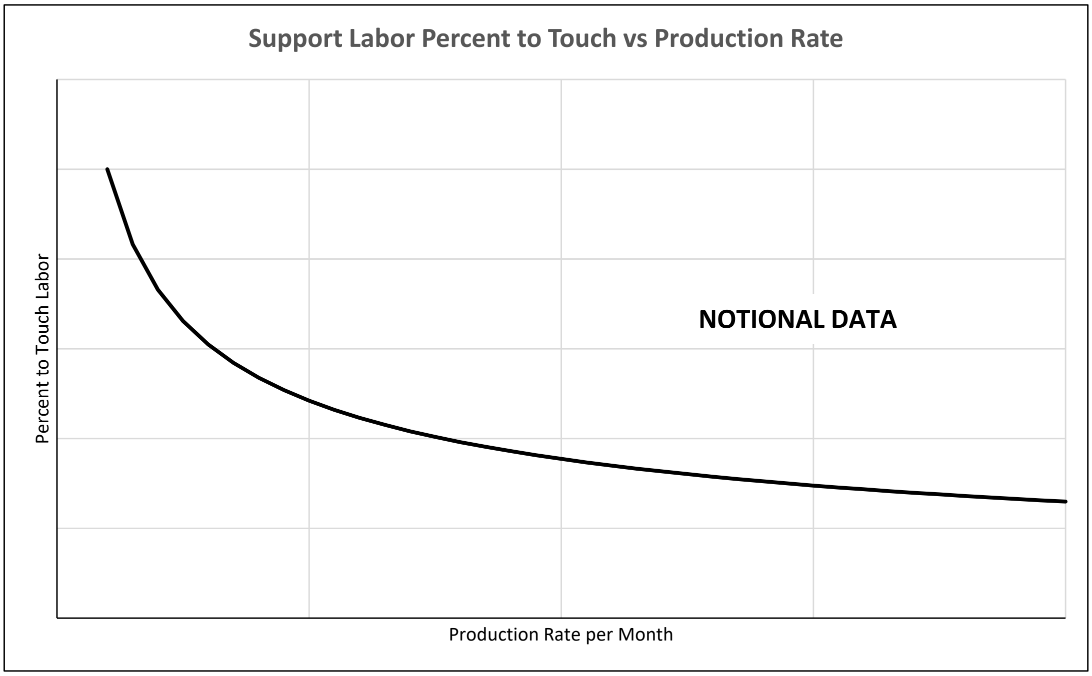
Exhibit 7.



Other tasks such as factory liaison and the investigation and resolution of quality nonconformances will be driven by production volumes. But these tasks usually have a fixed element as well. This is particularly true of the engineering function: no matter how low production rates go, a minimum staff must be maintained in order to ensure all the necessary engineering disciplines are covered if production is to continue at all.

It is sometimes assumed in the literature that staffing levels in engineering and tooling are fixed and do not vary at all regardless of rate. In the author's experience, this is not the case – there is a variable element – but at low production rates, the minimum staffing impacts are particularly prominent, just as a low tide exposes the rocks along the shore. Exhibit 8 is a notional example, showing the percent of support labor to touch labor plotted against production rate, with the highest ratios when production rates are at their lowest:

Exhibit 8.



So which driver – cumulative experience or production rate – is the primary influence? Unfortunately, this is particularly difficult to test empirically, not only because cumulative quantity and production rate are highly correlated. Another reason is that historical data does not always provide a clear distinction between recurring and non-recurring tooling, making it difficult to separate the impact of rate tooling for instance.

Not surprisingly, the small library of published literature on sustaining tooling and production rates is not particularly informative. Using acceptance span as a proxy for production rate, the 1974 RAND study did not find a statistically significant relationship between cumulative tooling costs and production rate. RAND dismissed this conclusion, calling it "dubious" on the grounds that additional tools are needed for higher production rates, which in turn should mean higher tooling hours. Examining only non-recurring tooling, RAND found a weak correlation between cumulative tooling hours and rate which was not statistically significant. It concluded: “Our analyses suggest…but do not confirm that cumulative tooling cost is not highly sensitive to rate of output.” (Large, 1974)

By contrast, the 2001 RAND analysis of MACDAR aircraft calculated an average cumulative quantity slope of 77% and rate slope of 75% -- and found the rate slope coefficient statistically significant at a 95% confidence level, the only cost element it examined for which this was the case. (Younossi, 2001)

The intersection of production rate and sustaining tooling (and engineering, as we shall see) is an area which has been sadly neglected in published research and is ripe for a reexamination.

ENGINEERING LABOR

Engineering labor includes hours for the design, analysis and test of a product. Non-recurring engineering covers the initial design, analysis and test as well as the incorporation of major engineering changes. Recurring engineering covers drawing maintenance and corrections of errors, incorporation of minor engineering changes, and manufacturing liaison.

There is no suggestion that production rates have a measurable impact on non-recurring engineering hours. That is driven largely by the technical complexity of the engineering design and test itself, and parametric estimators have long relied on variables such as weight and speed (in the case of aircraft) to measure that complexity.

On the recurring side, to reiterate comments made in the tooling section, it is likely that the passage of time plays at least as important a role in sustaining engineering labor hours. It is also likely that sustaining engineering is impacted by minimum staffing considerations at low rates and the need to keep a minimum number of engineers for each discipline, i.e., aerodynamics, stress, thermodynamics, propulsion, etc. The 1974 RAND study tips its hat to such considerations, arguing: “The essential point on which everyone appears to agree is that a low production rate will result in an increased number of engineering hours." (Large, 1974)

Using acceptance span as a proxy for production rate, the 1974 RAND study found a statistically significant relationship (at a 90% confidence level) between cumulative engineering hours and acceptance spans – that is, programs with slower production rates, i.e., longer acceptance rates, had higher cumulative engineering hours. However, RAND was suspicious of the size of the production rate exponents and did not recommend it for projection purposes. Nonetheless, it acknowledged a relationship between engineering hours and rate: "Sustaining engineering costs are almost directly proportional to program length, which is a function of production rate." (Large, 1974)

Almost three decades later, however, RAND came to the opposite conclusion. The 2001 RAND analysis of MACDAR aircraft calculated an average cumulative quantity slope of 71% and rate slope of 88%. The rate slope was not statistically significant at the 90% or 95% confidence level. (Younossi, 2001)

Here we have a neat reversal of findings – the 1974 RAND study found no statistical evidence of a relationship between tooling and production rate, yet the 2001 RAND study did; but while the 1974 study found a significant correlation between engineering and production rate, the 2001 study did not!

QUALITY ASSURANCE

Quality assurance is the inspection of manufactured items to ensure they meet the quality specifications. In addition to inspection itself, it usually includes the determination of specifications, establishing the methods and processes of inspection, and the maintenance of quality records.

Quality assurance is frequently estimated as a percentage of manufacturing hours, which suggests they will respond similarly to manufacturing hours to changes in production rate. However, this is a function where little formal study has been performed. The 1974 RAND study did not examine quality assurance at all. The 2001 RAND analysis of MACDAR aircraft calculated an average cumulative quantity slope of 85% and rate slope of 95%. The rate slope was not statistically significant at the 90% or 95% confidence level. (Younossi, 2001)

MANUFACTURING MATERIALS

While limited research on the relationship between unit cost and production rate has been performed for the support labor functions, even less has been performed for manufacturing materials. The 1974 RAND analysis is the only study the author has found which addresses this subject at all.

By material, we mean raw and semifabricated material, small purchased parts (such as valves, electrical fittings and fasteners) and purchased equipment (batteries, actuators and instruments). It specifically excludes major avionics and subsystems, i.e., radar, communications / navigation, et al. It also excludes build-to-print structural parts. For such items, the impact of rate would be expected to fall along the same direct labor and indirect costs categories as discussed in this paper.

Materials are considered to have relatively flat improvement curves – the common range is 85% to 95%. Two major drivers are commonly identified. First, scrappage and material waste are reduced over time as manufacturing processes become more efficient. Second -- and more relevant to our subject -- suppliers generally provide cost discounts for sufficiently large quantities of materials. (Large, 1974) Conversely, at low production rates, companies may find minimum buy quantities requiring, for example, that certain fasteners can only be bought at a minimum quantity of, say, one thousand per order even though a lesser quantity is actually needed by the program.

Production rate might be expected to influence raw material unit cost by triggering larger quantity discounts from raw material and hardware suppliers. It is also suggested the higher production rates induce OEMs to offload more work to smaller manufacturers with low overheads and low costs.

However, benefit from higher production rates to improvement curve slopes is not apparent. An analysis of aircraft material learning curve slopes and production rates (as measured by the number of months required to accept the 100th aircraft) shows very little apparent impact. On the other hand, RAND did find a larger impact of production rate on the cost of raw materials, purchased parts, and purchased equipment on missile programs. (Large, 1974)

RAND notes the difficulty of analyzing material costs due to the need to adjust for inflationary impacts over time, arguing that these sometimes artificial adjustments introduce an additional element of uncertainty to the analysis. Similar to its conclusions on manufacturing, RAND concluded: “On the evidence it appears that in fact rate may have some effect, but a more detailed study would be required to determine why that should be true and how important that effect is.” (Large, 1974) But in the subsequent 40 years, no one has taken up the call for such a study.

OVERHEAD / INDIRECT COSTS

Another area where there is little published research are indirect costs, such as overhead, general & administrative (G&A) costs, and cost of money. This is curious because indirect costs are generally the single largest component of cost. Indirect costs alone average 53% of contract costs in the defense industry. By contrast, less than 30% of product cost is touch labor or direct material. (Saha, 2002) Furthermore, at least some analysts believe overhead costs are leading contributors to the rate effect. (Dorsett, 1989)

For this paper, we will treat “overhead” and “indirect cost” as synonymous. By indirect costs, we mean costs which are necessary to the overall business operation, but at the same time do not show a direct relationship to any particular cost objective. Indirect costs are typically allocated to direct end-use contracts on the basis of direct labor hours, direct material dollars, floor space or some other allocation bases. Direct costs, on the other hand, are costs incurred specifically for a contract.

Overhead is a mix of fixed, semi-fixed and variable costs. Examples of fixed costs would include depreciation, taxes, insurance, utilities, rents and professional services; semifixed costs would include data processing, allocation of corporate expenses, IRAD, B&P; variable costs would include indirect labor, machine maintenance, operating supplies, training expenses, and travel. (Large, 1974)

Indirect costs are of interest because of the sizable fixed element of costs. To the extent that costs are fixed, then increases or decreases in production rates will allocate those fixed costs over a larger or smaller base, inversely impacting unit cost. Having said as much, it is surprising so little published research has performed on overhead impacts. Unfortunately, the analyst faces multiple difficulties when analyzing overhead impacts:

1. Detailed data is typically unavailable. Industry jealously guards its indirect cost information over justifiable concerns of accidently providing valuable cost information to its competitors. The information that is available is usually at a very high-level, making detail analysis impossible.
2. Companies have differing accounting practices with regard to the definition of direct and indirect cost. Certain functions, such as industrial engineering, may be a direct cost at Company A but an indirect cost at Company B. This makes cross-company comparisons difficult.
3. Accounting changes over time may move a given element from direct to indirect, or vice versa, over a period of time. Changes in accounting practices can complicate a time series analysis, or even invalidate it.

Nonetheless, there are at least two studies of the relationship between overhead cost and production rate. The first is a NAVAIR analysis of 15 aircraft manufacturers from 1975-1986 using data from the

Plant-Wide Data Reports (DD 1921-3) conducted by Thomas Gilbride. His analysis constructed macro-level overhead models for manufacturing, engineering, material and G&A. After conversion to constant year base dollars, percent changes in the business base were correlated to changes in overhead rates. Gilbride found significant relationships between business base and overhead rates, to the effect:

- A 10 percent increase in business base drove:
  - a 3.5 percent decrease in manufacturing overhead rates,
  - a 1.7 percent decrease in engineering overhead rates,
  - a 5.8 percent decrease in material overhead rates, and
  - a 4.6 percent decrease in G&A rates.
- Similarly, a 10 percent decrease in business base drove:
  - a 4.9 percent increase in manufacturing overhead rates,
  - a 6.8 percent increase in engineering overhead rates,
  - a 8.4 percent increase in material overhead rates, and
  - a 10.5 percent increase in G&A rates. (Dorsett, 1989)

This inverse relationship between business base and overhead rates is consistent with the rate effect model, provided that we assume that changes in business base are, in turn, driven by changes in production rates.

The second study comes from the 1974 RAND study. In it, RAND obtained overhead data from five aerospace companies over varying periods from 1960 to 1972. Similar to the Gilbride study, RAND analyzed the relationship between percent changes in overhead rates related to percent changes in direct labor cost, after accounting for inflationary impacts. RAND concluded that a 4 percent increase in direct labor caused a 1 percent decrease in the overhead rate, and vice versa.

In a secondary analysis, RAND examined overhead cost as a function of total recurring cost for a sample of 45 production lots of aircraft over the 1953-1972 time period. The results showed that the ratio of overhead cost to total cost decreased when total cost increased -- a confirmation of its earlier conclusion on the relationship between the movement of overhead costs to changes in business base. (Large, 1974)

In its conclusion, RAND emphasized the chain of causality that ultimately drives indirect costs. "While it may seem a fine distinction, we cannot say that production rate per se affects overhead costs. Rate affects volume of business, and the effect of volume on overhead can be appreciable." (Large, 1974)

CONCLUSION

What can we conclude from all this?

Exhibit 9 below summarizes the impact of production rate on unit costs by functional area and identifies if the changes in production rates are positively or negatively correlated with unit cost and apparent strength of that relationship. For example, in the long term, changes in production rate are inversely correlated with manufacturing labor hours (i.e., an increase in production rate decreases manufacturing hours per unit) but only weakly. On the other hand, changes in production rates are strongly and inversely correlated with overhead costs. Interestingly, it appears any significant change in production rate – either an increase or a decrease – adversely impacts manufacturing unit costs, at least in the short run. When it comes to total weapon system cost – the summation of all of these functional cost categories – there appears a moderate to weak correlation between production rate and unit cost. Because of the statistical uncertainty surrounding much of the published analysis, however, it is difficult to generalize on the magnitude.

Exhibit 9.

Functional Area	Impact of Production Rate on Unit Cost			
	Strong	**Moderate**	**Weak**	**None or Uncertain**
Manufacturing (Short-Term)	Increase in hours for rate changes, positive or negative			
Manufacturing (Long-Term)			Inversely correlated	
Tooling (Rate)	Positively correlated			
Tooling (Sustaining)		Inversely correlated		
Engineering (Non-Recurring)				None apparent
Engineering (Sustaining)		Inversely correlated		
Quality Assurance				Insufficient evidence
Materials			Inversely correlated	
Overhead / Indirect	Inversely correlated			
Total Weapon System		Inversely correlated		

Three salient facts stand out about the published evidence.

First, there is a significant area of grey around these conclusions. Different authors have come to contradictory conclusions – sometimes looking at the same basic data! – and most studies have suffered from an inability to tease strong conclusions from highly collinear data.

Second, outside of manufacturing, there are a number of functional areas where only one or two studies have been performed. The areas of support labor, overhead and materials are seriously underrepresented in terms of the number and depth of studies examining the relationship of unit cost to production rate (indeed, on the broader subject of cost improvement in general). This cries out for future research to re-examine these neglected areas.

Third, the astute reader will note that most of these studies were performed during the late 1960's through the 1980's. Since then there has been very limited amount of new research published on the subject. Clearly we cannot say the issue has been settled, although some cost analysts have pushed ahead on the brave assumption that there is a proven relationship which can be incorporated into cost estimates. Perhaps the subject has fallen out of favor; or perhaps there is only limited new data to analyze – after all, the quantity of new DoD hardware programs to analyze has dropped substantially since the Reagan era. But this question is not limited to Defense Department hardware; indeed, many rich examples should exist outside the defense industry, and perhaps it is time to try and mine this vein of data.

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Biography

Brent Johnstone is a production air vehicle cost estimator at Lockheed Martin Aeronautics Company in Fort Worth, Texas. He has 29 years' experience in the military aircraft industry, including 25 years as a cost estimator. He has worked on the F-16 program and since 1997 has been the lead Production Operations cost estimator for the F-35 program. He has a Master of Science from Texas A&M University and a Bachelor of Arts from the University of Texas at Austin.